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Zahri, N.N.A.H.[a] , Nordin, A.N.[a] , Azlan, N.Z.[b] , Hassan, I.H.[c] , Tung, L.H.[d] , Lim, L.M.[d] , Samsudin, Z.[d]

Wearable strain sensors: design shapes, fabrication, encapsulation and performance evaluation methods
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[a] Electrical and Computer Engineering Dept., International Islamic University Malaysia, Kuala Lumpur, Malaysia
[b] Department of Mechatronics Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia
[c] Mechatronics Department, Ahmadu Bello University, Zaria, Nigeria
[d] Manufacturing Technology and Innovation, Jabil Circuit Sdn. Bhd., Bayan Lepas Industrial Park Phase 4, Penang, 11900, Malaysia

Abstract
Highly durable, stretchable, sensitive and biocompatible wearable strain sensors are crucial for healthcare, sports, and robotic applications. While strain sensor designs, fabrication and testing methods have been widely discussed by researchers, not many have discussed sensor improvements via implementing designs and protection layers that make the sensor more resilient. This paper will focus on sensor designs (straight line, U-shape, serpentine, and kirigami) and material selection that can provide better performance. Theoretical equations and calculations to indicate how the design shapes contribute to providing better performance are also included. An important aspect which is not often explored is having encapsulation layers which can significantly reduce the formation of cracks when the sensor is subjected to mechanical stress and bending. This review will include post-fabrication steps that are necessary to incorporate protection layers for wearable sensors. Due to the curvilinear shapes of wearable sensors that often need to be in close contact with human skin, reliability and durability testing often differs greatly from that of traditional strain sensors. Recent techniques for performance evaluation specific to wearable sensors such as cyclic stretching, bending, stretch till failure, washability, signal latency, and tensile tests were also discussed in detail. This includes experimental setup and duration of testing and its significance was described. To ensure device safety for the user, biocompatibility assessments need to be made. In this review, cytotoxicity test methods such as trypan blue, cell proliferation and MTT assay were compared and evaluated. By consolidating recent developments, this paper aims to provide researchers and practitioners with a comprehensive understanding of the advancements, and future directions in this rapidly evolving field. © 2024 RSC.

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References

- Zhang, S., Chhetry, A., Zahed, M.A., Sharma, S., Park, C., Yoon, S., Park, J.Y.
(2022) *npj Flexible Electron.*, 6, pp. 1-12.

- Zhao, Z., Li, Q., Dong, Y., Gong, J., Li, Z., Qiao, X., Zhang, J.
(2021) *Energy Technol.*, 9, pp. 1-13.

- He, Y., Zhou, M., Mahmoud, M.H.H., Lu, X., He, G., Zhang, L., Huang, M., Azab, I.H.E.
(2022) *Adv. Compos. Hybrid Mater.*, 5, pp. 1939-1950.

- Nguyen, T.N., Chun, S., Kim, J.
(2023) *J. Ind. Text.*, 53, pp. 1-17.

- Geng, W., Cuthbert, T.J., Menon, C.
(2021) *ACS Appl. Polym. Mater.*, 3, pp. 122-129.

- Wang, L., Xu, T., Fan, C., Zhang, X.
(2021) *iScience*, 24, p. 102028.
33490926

- Kim, Y.G., Song, J.H., Hong, S., Ahn, S.H.
(2022) *npj Flexible Electron.*, 6, pp. 1-8.

- Pei, Z., Zhang, Q., Yang, K., Yuan, Z., Zhang, W., Sang, S.
(2021) *Adv. Mater. Technol.*, 6, pp. 1-7.
https//dx.doi.org/0.002/ADMT.00038

- Sencadas, V., Mutlu, R., Alici, G.
(2017) *Sens. Actuators, A*, 266, pp. 56-64.

- Tang, C., Xu, M., Yi, W., Zhang, Z., Occhipinti, E., Dong, C., Ravenscroft, D., Occhipinti, L.G.
(2024) *npj Flexible Electron.*, 8, pp. 1-11.

- Tang, W., Yan, T., Wang, F., Yang, J., Wu, J., Wang, J., Yue, T., Li, Z.
(2019) *Carbon*, 147, pp. 295-302.

- Zhang, D., Tang, Y., Zhang, Y., Yang, F., Liu, Y., Wang, X., Yang, J., Zheng, J.
(2020) *J. Mater. Chem. A*, 8, pp. 20474-20485.

- Yang, C., Yin, J., Chen, Z., Du, H., Tian, M., Zhang, M., Zheng, J., Deng, K.
(2020) *Macromol. Mater. Eng.*, 305, p. 2000479.

- Zhang, Q., Liu, L., Zhao, D., Duan, Q., Ji, J., Jian, A., Zhang, W., Sang, S.
(2017) *Nanomaterials*, 7 (12), p. 424.
2920518

- Zhai, W., Zhu, J., Wang, Z., Zhao, Y., Zhan, P., Wang, S., Zheng, G., Shen, C.
(2022) *ACS Appl. Mater. Interfaces*, 14, pp. 4562-4570.
35020359

- Liao, X., Zhang, Z., Kang, Z., Gao, F., Liao, Q., Zhang, Y.
(2017) *Mater. Horiz.*, 4, pp. 502-510.

- Souri, H., Bhattacharyya, D.
(2019) *Sens. Actuators, A*, 285, pp. 142-148.

- Souri, H., Banerjee, H., Jusufi, A., Radacsi, N., Stokes, A.A., Park, I., Sitti, M., Amjadi, M.
(2020) *Adv. Intell. Syst.*, 2, p. 2000039.

- Afsarimanesh, N., Nag, A., Sarkar, S., Sabet, G.S., Han, T., Mukhopadhyay, S.C.
(2020) *Sens. Actuators, A*, 315, p. 112355.

- Liu, Y., Wang, H., Zhao, W., Zhang, M., Qin, H., Xie, Y.
(2018) *Sensors*, 18, p. 645.
29470408

- Zavanelli, N., Kwon, K., Yeo, W.H.
(2023) *IEEE Open J. Eng. Med. Biol.*, pp. 1-35.

- Si, Y., Chen, S., Li, M., Li, S., Pei, Y., Guo, X.
(2022) *Adv. Intell. Syst.*, 4, p. 2100046.

- Wu, S., Peng, S., Yu, Y., Wang, C.H.
(2020) *Adv. Mater. Technol.*, 5 (2), p. 1900908.

- Duan, L., D'hooge, D.R., Cardon, L.
(2020) *Prog. Mater. Sci.*, 114, p. 100617.

- Qiu, A., Li, P., Yang, Z., Yao, Y., Lee, I., Ma, J.
(2019) *Adv. Funct. Mater.*, 29, p. 1806306.

- Yadav, A., Yadav, N., Wu, Y., RamaKrishna, S., Hongyu, Z.
  (2023) *Mater. Adv.*, 4, pp. 1444-1459.

- Wang, H., Liu, J., Cui, H., Liu, Y., Zhu, J., Wang, H., Song, G., Chen, D.
  (2021) *ACS Appl. Electron. Mater.*, 3, pp. 1758-1770.

- Liu, P., Pan, W., Liu, Y., Liu, J., Xu, W., Guo, X., Liu, C., Huang, Y.
  (2018) *Compos. Sci. Technol.*, 159, pp. 42-49.

- Hu, Y., Zhao, T., Zhu, P., Zhang, Y., Liang, X., Sun, R., Wong, C.-P.
  (2018) *Nano Res.*, 11, pp. 1938-1955.

- Souri, H., Bhattacharyya, D.
  (2018) *Mater. Des.*, 154, pp. 217-227.

- Wang, J., Liu, Y., Su, S., Wei, J., Rahman, S.E., Ning, F., Christopher, G., Qiu, J.
  (2019) *Polymer*, 11, p. 1873.

- Sun, H., Fang, X., Fang, Z., Zhao, L., Tian, B., Verma, P., Maeda, R., Jiang, Z.
  (2022) *Microsyst. Nanoeng.*, 8, pp. 1-10.
  350760

- Gao, W.C., Wu, W., Chen, C.Z., Zhao, H., Liu, Y., Li, Q., Huang, C.X., Zhang, Q.C.
  (2022) *ACS Appl. Mater. Interfaces*, 14, pp. 1874-1884.
  34937333

- Yang, J., Ling, K., Liu, L., Zeng, X., Xu, X., Li, Z., He, P.
  (2022) *IEEE Sens. J.*, 22, pp. 13937-13944.

- Qu, M., Qin, Y., Sun, Y., Xu, H., Schubert, D.W., Zheng, K., Xu, W., Nilsson, F.
  (2020) *ACS Appl. Mater. Interfaces*, 12, pp. 42140-42152.
  32816448

- Wang, R., Xu, W., Shen, W., Shi, X., Huang, J., Song, W.
  (2019) *Inorg. Chem. Front.*, 6, pp. 3119-3124.

- Fu, X., Ramos, M., Al-Jumaily, A.M., Meshkinzar, A., Huang, X.
  (2019) *J. Mater. Sci.*, 54, pp. 2170-2180.

- Amjadi, M., Yoon, Y.J., Park, I.
  (2015) *Nanotechnology*, 26, p. 375501.
  303117

- Qiu, A., Aakyiir, M., Wang, R., Yang, Z., Umer, A., Lee, I., Hsu, H.Y., Ma, J.
  (2020) *Mater. Adv.*, 1, pp. 235-243.

- Xu, K., Lu, Y., Honda, S., Arie, T., Akita, S., Takei, K.
  (2019) *J. Mater. Chem. C*, 7, pp. 9609-9617.

- Muth, J.T., Vogt, D.M., Truby, R.L., Mengüç, I., Kolesky, D.B., Wood, R.J., Lewis, J.A., Wood, R.J.
  (2014) *Adv. Mater.*, 26 (36), pp. 6307-6312.
  24934143

- Li, Y., Samad, Y.A., Taha, T., Cai, G., Fu, S.Y., Liao, K.
  (2016) *ACS Sustainable Chem. Eng.*, 4, pp. 4288-4295.

- Liu, H., Jiang, H., Du, F., Zhang, D., Li, Z., Zhou, H.
  (2017) *ACS Sustainable Chem. Eng.*, 5, pp. 10538-10543.

- Wang, S., Cheng, H., Yao, B., He, H., Zhang, L., Yue, S., Wang, Z., Ouyang, J.
  (2021) *ACS Appl. Mater. Interfaces*, 13, pp. 20735-20745.

33900075

- Azadi, S., Peng, S., Moshizi, S.A., Asadnia, M., Xu, J., Park, I., Wang, C.H., Wu, S.
(2020) *Adv. Mater. Technol.*, 5 (11), p. 2000426.

- Cai, Y., Qin, J., Li, W., Tyagi, A., Liu, Z., Hossain, M.D., Chen, H., Luo, Z.
(2019) *J. Mater. Chem. A*, 7, pp. 27099-27109.

- Xu, H., Lv, Y., Qiu, D., Zhou, Y., Zeng, H., Chu, Y.
(2019) *Nanoscale*, 11, pp. 1570-1578.
30644941

- Demidenko, N.A., Kuksin, A.V., Molodykh, V.V., Pyankov, E.S., Ichkitidze, L.P., Zaborova, V.A., Tsymbal, A.A., Gerasimenko, A.Y.
(2022) *Bioengineering*, 9 (1), p. 9010036.
3504745

- Cai, Y., Qin, J., Li, W., Tyagi, A., Liu, Z., Hossain, M.D., Chen, H., Luo, Z.
(2019) *J. Mater. Chem. A*, 7, pp. 27099-27109.

- Ke, S.H., Guo, P.W., Pang, C.Y., Tian, B., Luo, C.S., Zhu, H.P., Wu, W.
(2020) *Adv. Mater. Technol.*, 5 (5), p. 1901097.

- Ertugrul, I., Ulkir, O., Ersoy, S., Ragulskis, M.
(2023) *Polymers*, 15 (4), p. 991.
3685027

- Mustapha, N.H.M., Razif, M.R.M., Nasir, S.H., Nordin, I.N.A.M., Mi, Y.T.
(2023) *Jurnal Teknologi*, 85 (4), pp. 27-35.

- Kantarak, E., Rucman, S., Kumpika, T., Sroila, W., Tippo, P., Panthawan, A., Sanmuangmoon, P., Singjai, P.
(2020) *Appl. Compos. Mater.*, 27, pp. 955-968.

- Ke, S.H., Guo, P.W., Pang, C.Y., Tian, B., Luo, C.S., Zhu, H.P., Wu, W.
(2020) *Adv. Mater. Technol.*, 5 (5), p. 1901097.
https//dx.doi.org/10.1002/ADMT.20

- Gong, X., Huang, K., Wu, Y.H., Zhang, X.S.
(2022) *Sens. Actuators, A*, 345, p. 113821.

- Qi, X., Ha, H., Hwang, B., Lim, S.
(2020) *Appl. Sci.*, 10, p. 6983.

- Anderson, N., Szorc, N., Gunasekaran, V., Joshi, S., Jursich, G.
(2019) *Sens. Actuators, A*, 290, pp. 1-7.

- Yang, X., Gui, J., Dong, C., Zhao, J., Xu, R.
(2023) *ACS Appl. Nano Mater.*, 6, pp. 21679-21687.

- Yang, X., Gui, J., Dong, C., Zhao, J., Xu, R.
(2023) *ACS Appl. Nano Mater.*, 6, pp. 21679-21687.

- Jeong, H., Lim, S.
(2016) *Sensors*, 16, p. 1839.
27827833

- Anderson, N., Szorc, N., Gunasekaran, V., Joshi, S., Jursich, G.
(2019) *Sens. Actuators, A*, 290, pp. 1-7.

- Han, T., Kundu, S., Nag, A., Xu, Y.
(2019) *Sensors*, 19 (7), p. 1706.

https//dx.doi.org/10.3390/S0 30945

- Coste, A., Oliveira Da Fonseca, L., Guillermo, J., Alfaro, C., Trejos, A.L.
(2023) *Sensors*, 23, p. 1503.
36772542

- Xia, Y., Zhang, Q., Wu, X.E., Kirk, T.V., Chen, X.D.
(2019) *Sensors*, 19, p. 4553.
31635124

- Li, X., Koh, K.H., Farhan, M., Lai, K.W.C.
(2020) *Nanoscale*, 12, pp. 4110-4118.
32022071

- Lu, W., Mustafa, B., Wang, Z., Lian, F., Yu, G.
(2022) *Nanomaterials*, 12 (5), p. 871.
https//dx.doi.org/10.3390/NANO00/S1 326939

- Zhao, Y., Ren, M., Shang, Y., Li, J., Wang, S., Zhai, W., Zheng, G., Shen, C.
(2020) *Compos. Sci. Technol.*, 200, p. 108448.

- Aslanidis, E., Skotadis, E., Moutoulas, E., Tsoukalas, D.
(2020) *Sensors*, 20 (9), p. 2584.
32370042

- Fang, F., Wang, H., Wang, H., Gu, X., Zeng, J., Wang, Z., Chen, X., Chen, M.
(2021) *Micromachines*, 12, p. 252.
33804498

- Song, Y.X., Xu, W.M., Rong, M.Z., Zhang, M.Q.
(2019) *J. Mater. Chem. A*, 7, pp. 2315-2325.

- Madhavan, R.
(2022) *J. Mater. Sci.: Mater. Electron.*, 33, pp. 3465-3484.

- Qiu, A., Aakyiir, M., Wang, R., Yang, Z., Umer, A., Lee, I., Hsu, H.Y., Ma, J.
(2020) *Mater. Adv.*, 1, pp. 235-243.

- Zhou, J., Guo, X., Xu, Z., Wu, Q., Chen, J., Wu, J., Dai, Y., Huang, Z.
(2020) *Compos. Sci. Technol.*, 197, p. 108215.

- Yan, C., Wang, J., Kang, W., Cui, M., Wang, X., Foo, C.Y., Chee, K.J., Lee, P.S.
(2014) *Adv. Mater.*, 26, pp. 2022-2027.
24343930

- Yong, K., De, S., Hsieh, E.Y., Leem, J., Aluru, N.R., Nam, S.W.
(2020) *Mater. Today*, 34, pp. 58-65.

- Li, S., Liu, G., Li, R., Li, Q., Zhao, Y., Huang, M., Zhang, M., Su, Y.
(2022) *ACS Nano*, 16, pp. 541-553.
34919398

- Hossen, S., Nordin, A.N., Suhaimi, M.I., Ming, L.L., Azlan, N.Z., Rahim, R.A., Riza, M.S., Samsudin, Z.
(2024) *IFMBE Proceedings*, 107, pp. 65-72.
and pp

- Zhou, J., Guo, X., Xu, Z., Wu, Q., Chen, J., Wu, J., Dai, Y., Huang, Z.
(2020) *Compos. Sci. Technol.*, 197, p. 108215.
https//dx.doi.org/10.1016/J.COMPSCITECH..

- Araromi, O.A., Graule, M.A., Dorsey, K.L., Castellanos, S., Foster, J.R., Hsu, W.H., Passy, A.E., Wood, R.J.
  (2020) *Nature*, 587 (7833), pp. 219-224.
  33177670

- Huang, Y.T., Huang, S.C., Hsu, C.C., Chao, R.M., Vu, T.K.
  (2012) *Sensors*, 12, pp. 3269-3280.
  22737007

- Yong, K., De, S., Hsieh, E.Y., Leem, J., Aluru, N.R., Nam, S.
  (2020) *Mater. Today*, 34, pp. 58-65.

- Petz, P., Biermaier, C., Scharinger, J., Langer, J.
  (2023) *Conference Record - IEEE Instrumentation and Measurement Technology Conference*, p. 10175942.
  and p.

- Wiranata, A., Ohsugi, Y., Minaminosono, A., Kuwajima, Y., Maeda, S.
  (2022) *HardwareX*, 11, p. e00287.
  35509934

- Feng, R., Mu, Y., Zeng, X., Jia, W., Liu, Y., Jiang, X., Gong, Q., Hu, Y.
  (2021) *Sensors*, 21, p. 3969.
  342075

-
  Trypan Blue Staining Protocol|Creative Bioarray accessed 16 April 2024

- Sun, T., Jiang, Y.D., Duan, Z.H., Yuan, Z., Wang, Y., Tai, H.L.
  (2021) *Sci. China: Technol. Sci.*, 64, pp. 441-450.

- Sadeqi, A., Rezaei Nejad, H., Alaimo, F., Yun, H., Punjiya, M., Sonkusale, S.R.
  (2018) *IEEE Sens. J.*, 18, pp. 9137-9144.

- Zhou, Y., Zhan, P., Ren, M., Zheng, G., Dai, K., Mi, L., Liu, C., Shen, C.
  (2019) *ACS Appl. Mater. Interfaces*, 11, pp. 7405-7414.
  30698944

- Fan, Y., Zhao, H., Yang, Y., Yang, Y., Ren, T., Tu, H.
  (2022) *Front. Sens.*, 2, p. 815209.

- Zheng, Y., Li, Y., Zhou, Y., Dai, K., Zheng, G., Zhang, B., Liu, C., Shen, C.
  (2020) *ACS Appl. Mater. Interfaces*, 12, pp. 1474-1485.
  31825588

- Zhai, K., Wang, H., Ding, Q., Wu, Z., Ding, M., Tao, K., Yang, B.R., Wu, J.
  (2022) *Adv. Sci.*, 10 (6), p. 5632.

- Chen, X., Wang, F., Shu, L., Tao, X., Wei, L., Xu, X., Zeng, Q., Huang, G.
  (2022) *Mater. Des.*, 221, p. 110926.

- Fan, X., Wang, N., Wang, J., Xu, B., Yan, F.
  (2018) *Mater. Chem. Front.*, 2, pp. 355-361.

- Zahri, N.N.A.H., Nordin, A.N., Mansor, A.F.M., Rahim, R.A., Ralib, A.A.M., Suhaimi, M.I., Ming, L.L.
  (2023) *9th International Conference on Computer and Communication Engineering (ICCCE)*,
  and pp. 173-;176

- Tan, C., Dong, Z., Li, Y., Zhao, H., Huang, X., Zhou, Z., Jiang, J.W., Sun, B.
  (2020) *Nat. Commun.*, 11, pp. 1-10.

39652

- Strober, W.
(2015) *Curr. Protoc. Immunol.*, 111, p. A3B1.
26529666

- Salari, M., Mohseni Taromsari, S., Bagheri, R., Faghihi Sani, M.A.
(2019) *J. Mater. Sci.*, 54, pp. 4259-4276.

Correspondence Address
Nordin A.N.; Electrical and Computer Engineering Dept., Malaysia; email: nurnazihah.ahz@gmail.com

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